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Steam Plasma-Assisted Gasification of Organic Waste by Reactions with Water, CO_2 and O_2

M. Hrabovsky[1], M. Hlina[1], M. Konrad[1], V. Kopecky[1], O. Chumak[1], A. Maslani[1], T. Kavka[1], O. Zivny[1], G. Pellet[2]

[1]*Institute of Plasma Physics ASCR, Prague, Czech Republic*
[1]*Helmo Gramme, Liege, Belgium*

Abstract: Production of syngas by reaction of wood saw dust and wooden pellets with oxygen, carbon dioxide and water was studied in plasma reactor. Steam plasma was produced in dc arc torch stabilized by combination of water vortex and argon flow. Composition of syngas was compared with theoretical composition corresponding to thermodynamic equilibrium of the mixture of input reagents and plasma. Energy balance of the process is analyzed.

Keywords: Plasma gasification, steam plasma, syngas.

1. Introduction

Plasma gasification of organic materials for production of syngas is an alternative to conventional treatment of waste. For this application, the principal goal of the technology is production of fuel gases, principally mixture of carbon monoxide and hydrogen, called syngas. Thermal plasma offers possibility of decomposition of organics by pure pyrolysis in the absence of oxygen, or with stoichiometric amount of oxygen (gasification) to produce high quality syngas, with high content of carbon monoxide and hydrogen and minimum presence of other components. As production of fuel gas is the main goal of the technology, a quality of produced gas and an energy balance of the process are much more important than in case of waste treatment, where the principal goal is material destruction.

Plasma is a medium with the highest energy content and thus substantial lower plasma flow rates are needed to supply sufficient energy needed for gasification compared with other media used for this purpose. This results in minimum contamination and dilution of produced syngas by plasma gas and easy control of syngas composition. The other advantages are higher calorific value of the gas and reduction of unwanted contaminants like tar, CO_2, CH_4 and higher hydrocarbons, as well as wide choice of treated materials. The process can be used also for energy storage – electrical energy is transferred into plasma energy and then stored in chemical energy of produced gas.

This paper presents results of study of gasification of wood saw dust and wooden pellets by steam plasma assisted reaction with oxygen, carbon dioxide and water. Energy balance of the process is analyzed and composition of produced gas is compared with theoretically determined composition of complete gasification of mixture of input materials. Effect of material feed rate, material particle size, flow rate of added gases and energy available for material treatment on syngas properties was studied in experiments.

2. Experimental System

The principal scheme of experimental reactor is shown in **Fig. 1**. High enthalpy steam plasma was generated in dc arc torch with hybrid water/gas plasma torch [1]. Basic parameters of plasma torch are in **Table 1**. Wood saw dust

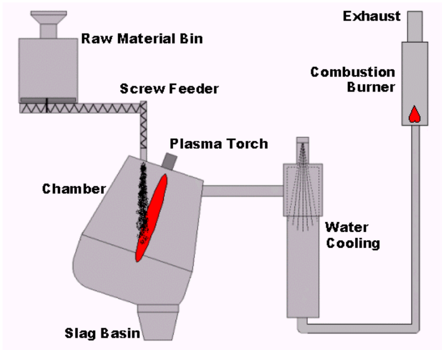

Fig. 1 Schematic of plasma reactor PlasGas.

and wooden pellets were supplied into plasma flow inside the reactor with internal volume 200 l [2, 3]. Water, CO_2, and oxygen were supplied into reactor volume to achieve stoichiometric composition of reactants for complete gasification. Gas produced in the reactor was fed into quenching tower where the temperature was rapidly reduced to 300 ^{0}C by water spray. After filtering and cleaning the produced gas was burned in the gas burner.

Table 1. Operation parameters of plasma torch

Arc current[A]	400
Arc power [kW]	115
Torch efficiency	0.6
Plasma flow rate [g/s]	0.45
Mean plasma enthalpy [MJ/kg]	153
Exit centerline temperature [K]	1 900

Measurements of temperatures and power losses in the reactor were made, composition of produced syngas in the reactor and at the output of quenching chamber were performed by mass spectrometer and analyzer of CO and H_2.

3. Theoretical calculation of reaction products

Principally all carbon and hydrogen atoms from biomass can be used for syngas production if biomass is heated to sufficiently high temperature. Maximum biomass to syngas conversion efficiency is achieved if all carbon is oxidized to CO. As most of biomass materials contain more carbon atoms than oxygen atoms, some oxygen has to be added to gasify all carbon. In our experiments we did it by addition of oxygen, carbon dioxide , or water.

We verify how close the experimental data can be to composition described by following three reactions:

a) Gasification by reaction with oxygen

$$biomass + \frac{(n_C - n_O)}{2} O_2 \Rightarrow n_C\,CO + n_{H_2}\,H_2 \tag{1}$$

b) Gasification by reaction with carbon dioxide

$$biomass + (n_C - n_O) CO_2 \Rightarrow (2n_C - n_O) CO + n_{H_2}\,H_2 \tag{2}$$

c) Gasification by reaction with water

$$biomass + (n_c - n_0) H_2O \Rightarrow n_c\,CO + (n_{H_2} + n_c - n_O) H_2 \tag{3}$$

where $n_C = c/M_C$, $n_{H2} = h/2M_H$ and $n_O = o/M_O$ are molar concentrations of carbon, hydrogen and oxygen in biomass with mass fractions of carbon, hydrogen and oxygen equal to c, h and o. For calculation of results presented in the following paragraph wood was represented by values $c = 0.523$, $h = 0.061$ and $o = 0.412$ [4]. In these calculations we took into account also water coming from humidity of wood samples and oxygen and hydrogen introduced to reactor by steam plasma.

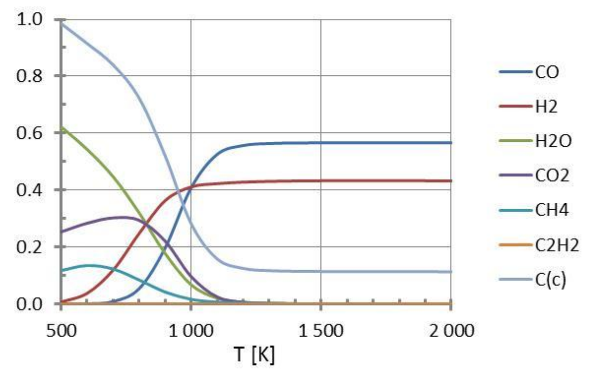

Fig. 2 Equilibrium composition of mixture of input reactants. Wood 30 kg/h, CO_2 85.4 slm, steam plasma 0.3 g/s.

The data about theoretical composition was obtained by calculating thermodynamic equilibrium composition of mixture of all reactants introduced into reactor in the experiment. The equilibrium composition of this heterogeneous system was calculated using the method described in [5], the input data for the calculations were taken from database [6]. An example of calculated composition for one set of experimental parameters is shown in **Fig. 2**. The composition corresponds to the experiment with wood saw dust with humidity 12.2% and feed rate 30 kg/hour. Molar fractions of main components of gas phase are shown in **Fig. 2** and a ratio C(s) of moles of carbon in solid phase to all moles in the gas phase. It can be seen that for temperatures above 1300 K the composition of reaction products is almost constant and main components are carbon monoxide and hydrogen. Therefore the temperature in the experimental reactor was kept between 1300 and 1400 K during the experiments.

4. Results

The measurements were done for fine wood saw dust with humidity 12.2% and wooden pellets with the diameter 9 mm and the length 10-15 mm. The results presented here were obtained at two feed rates of material 30 kg/h and 60 kg/h. Various combinations of oxidizing media (water, carbon dioxide and oxygen) were added, the molar ratio of input oxygen to input carbon was set to 1.1. The temperature in the reactor was during the experiment changing in dependence on input feed rates of reactants and varied in the range of 1200 to 1500 K.

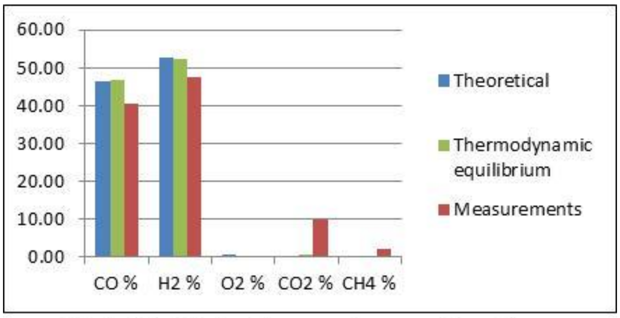

Fig. 3 Calculated and measured composition of syngas. Wood saw dust 30 kg/hour, water 70.4 ml/min.

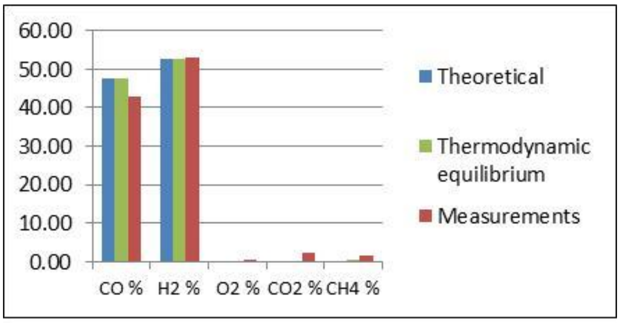

Fig. 4 Calculated and measured composition of syngas. Wood saw dust 60 kg/hour, water 140.8 ml/min.

In **Fig. 3** to **Fig. 6** measured composition of produced syngas is compared with calculated compositions for several sets of input parameters. Calculated values were obtained by computing thermodynamic equilibrium composition of mixture of input reactants as shown in **Fig. 2**, values marked as theoretical correspond to calculation of composition under the assumption that all carbon atoms are oxidized to CO, all hydrogen atoms forms H_2 molecules.

Fig. 3 and **Fig. 4** present resulting composition of syngas produced through reactions of wood saw dust with water for wood feeding rates 30 kg/h and 60 kg/h. It can be seen that change of feed rate from 30 kg/h and 60 kg/h resulted only in small change of syngas composition, the changes were within limits of measurement accuracy. In **Fig. 5** and **Fig. 6** results of reaction of wood saw dust with mixture of water with CO_2 and O_2 are shown. In all cases the measured composition was close to theoretical calculations, in experiments small amount of CO_2 and CH_4 was produced. The difference between two theoretical calculations was less than 1%.

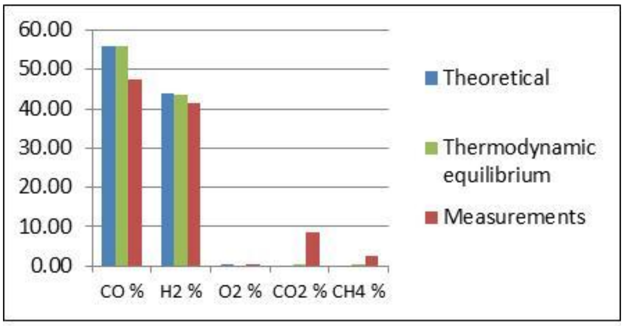

Fig. 5 Calculated and measured composition of syngas. Wood saw dust 30 kg/hour, CO_2 – 85.4 slm .

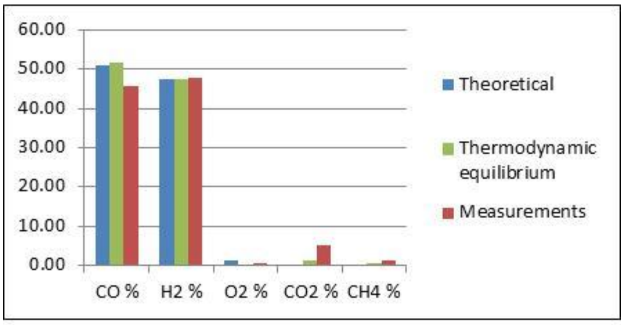

Fig. 6 Calculated and measured composition of syngas. Wood saw dust 30 kg/hour, O_2 - 44.2 slm .

For testing of an effect material particles size the experiments with wooden pellets were performed. Results for feeding rates 30 kg/h and 60 kg/h and addition of water are shown in **Fig. 7** and **Fig. 8**. The comparison of measurements for pellets with the length of up to 15 mm with results for very fine wood saw dust show that size of particles has almost no effect on resulting syngas composition. Also comparison of results for feeding rates 30 kg/h and 60 kg/h show no effect of feeding rate.

The gasification yield of carbon Y_C defined as a ratio of carbon moles in syngas to carbon moles in all inputs and gasification yield of hydrogen defined in the same way

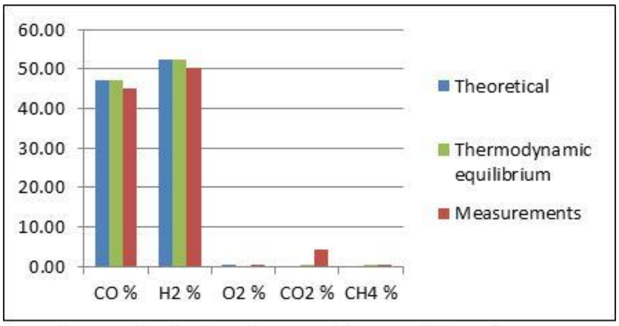

Fig. 7 Calculated and measured composition of syngas. Wood pellets 30 kg/hour, water 79.6 ml/min.

were determined from the feed rates of input reactants and flow rate of produced syngas. The flow rate of syngas was measured by Pitot tube flow meter and pressure difference flow meter. Both flow meters are based on measurement of pressure difference and as the difference is much smaller than strongly fluctuating stagnation pressure in

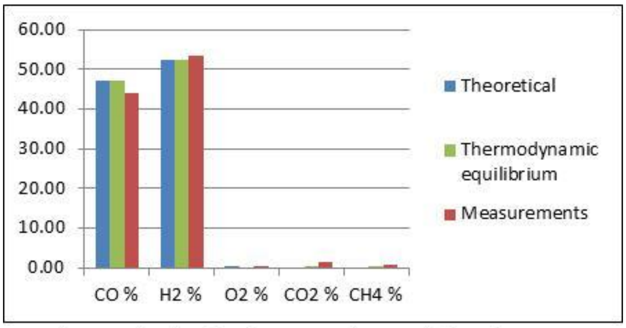

Fig. 8 Calculated and measured composition of syngas. Wood pellets 60 kg/hour, water 177 ml/min.

the reactor, the measurements error was high. The most reliable was determination of syngas flow rate from measured percentage of an inert gas (Ar) which was supplied into the reactor volume with known flow rate. The gasification yields determined by this measurement were for both carbon and hydrogen in the range 0.7 – 0.9.

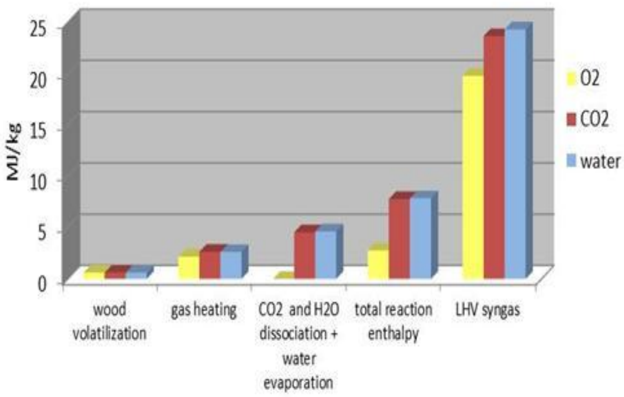

Fig. 9 Energy balance of gasification of 1 kg of dry wood by reactions with water, CO_2 and oxygen.

The energy balance of the process was analyzed on the basis of calculations of energy needed for wood gasification and energy for dissociation of water and carbon dioxide [3]. The total energy which has to be supplied by plasma for realization of endothermic process is composed of energy for wood volatilization, energy for dissociation of CO_2, evaporation and dissociation of water and energy needed to heat all reactants to the temperature in the reactor. The resulting energy balance for 1 kg of dry wood is shown in **Fig. 9** for reaction temperature $T_r = 1\,300$ K. The total reaction enthalpies for gasification process are 7.85 MJ/kg for water process, 7.77 MJ/kg for CO_2 process and 2.77 for O_2 process. Corresponding energy yields defined as ratio of low heating value of produced syngas to energy needed for gasification are 3.1, 3.0 and 7. 1, respectively. In our case the efficiency of the torch was 0.6, power loss to the reactor walls was 15 kW, therefore the power available for gasification was 54 kW. For wood with humidity 12.2% maximum feed rates corresponding to this power are 49 kg/h for oxygen process, and 28 kg/h for CO_2 and water processes. For feed rates 60 kg for CO_2 and water processes the wall temperatures of the reactor slowly decreased which means that additional energy was supplied from the pre/heated insulating walls of the reactor with high heat capacity. For 30 kg/h the wall temperatures were increasing for oxygen process and approximately constant for the two other processes, which corresponds to calculated values following from energy balances in **Fig. 9**.

5. Conclusions

Production of syngas by reaction of wood saw dust and wooden pellets with oxygen, carbon dioxide and water was studied in plasma reactor. High enthalpy steam plasma was produced in dc arc torch stabilized by combination of water vortex and argon flow. Composition of syngas was compared with theoretical composition corresponding to thermodynamic equilibrium of the mixture of input reagents and plasma, and to composition determined from the assumption that all carbon and hydrogen atoms in the material are transformed to gas mixture of carbon monoxide and hydrogen. The two theoretical computations give almost the same results for temperatures above 1 300 K. Measured syngas composition at experiments with reactor temperatures between 1 300 K and 1 500 K was close to the theoretical composition for all three processes. Change of feed rate from 30 kg/h to 60 kg/h has almost no effect on measured syngas composition. Also increase of size of wood particles from fine dust to pellets with length 10 – 15 mm has no effect on resulting gas composition.

It was proved by the experiments that syngas with high content of hydrogen and carbon monoxide can be obtained by gasification in steam plasma. The syngas composition can be controlled by a choice of oxidizing medium. It is also possible to combine oxidizing media to achieve proper gas composition. Thus, the process can be used for production of clean syngas with controlled composition from waste organic materials. The process can be used also for CO_2 reforming and for energy storage. Electrical energy is transformed in plasma torch into plasma enthalpy which is used for CO_2 reforming in gasification reactor and which is deposited in chemical energy of syngas.

Acknowledgement

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